The New England Seismic Network

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1.0 Abstract

From February 1, 2007 to January 31, 2010 Weston Observatory continued to operate a regional seismic network to monitor earthquake activity in New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) and vicinity. As of January 31, 2010, the New England Seismic Network (NESN) of Weston Observatory consisted of 15 broadband stations. The purpose of this monitoring is to compile a complete database of earthquake activity in New England and vicinity to as low a magnitude as possible in order to understand the causes of the earthquakes in the region, to assess the potential for future damaging earthquakes, and to better constrain the patterns of strong ground motions from earthquakes in the region. The NESN coordinates earthquake monitoring in the northeastern U.S. (NEUS) with the Lamont Cooperative Seismic Network (LCSN) of Lamont-Doherty Earth Observatory as part of the Advanced National Seismic Network (ANSS) northeast center for earthquake monitoring (ANSS-NE). It also coordinates its activities with the National Earthquake Information Center (NEIC) of the US Geological Survey in Golden, CO and with the Earthquakes Canada group of the Geological Survey of Canada (GSC) in Ottawa, Ontario.

There were 214 local and regional earthquakes with magnitudes from 0.3 to 4.2 that were detected and located by the NESN network from February 1, 2007 to January 31, 2010, along with many microearthquakes and some other signals that were possible earthquakes; 107 earthquakes were centered in (or offshore of) New England proper. From 2007 to 2010 the earthquake activity in New England remained at a relatively low rate, especially when compared to the very active time period from 1979-1984. No earthquakes with M≥3.0 were detection in New England from February 1, 2007 to January 31, 2010, which represents an unusual lull in the stronger earthquakes in the region as compared to the long-term average. The higher rate of small earthquakes from 1979 and 1984 compared to more recent times corresponded to a time period when several earthquake with M≥5.0 took place in northeastern North America, and when several earthquakes with M≥4.0 took place in New England. This evidence may suggest that there is a higher probability of earthquakes with larger magnitudes in northeastern North American during time periods when there is a higher rate of small earthquakes throughout New England and vicinity.

2.0 Importance of Earthquake Hazard Monitoring for Seismic Hazard Assessment and Earthquake Hazard Mitigation Measures in the NEUS

The NEUS is one of the most seismically active areas east of the Rocky Mountains. This area has a long and continuous history of earthquake activity going back to earliest colonial times, and it has experienced strong, damaging earthquakes on several occasions, most notably in 1638, 1663, 1727, 1737, 1755, 1884, 1904, 1940 and 1944. For the NEUS, the earthquake hazard is most clearly illustrated by the 1755 Cape Ann earthquake, which had a magnitude of about 6.0-6.2 (Ebel, 2006). This earthquake did significant damage to masonry structures in Boston; Ebel (2006) estimated peak ground accelerations (pga) to be in the range of about .08g to .11g, which corresponds approximately to the 5% in 50 yr ground motion on the 2008 USGS National Seismic Hazard maps. A recurrence today of the 1755 earthquake would probably lead to several billion dollars damage just within the city limits of Boston, with additional damage in the surrounding suburbs (based on a 1996 HAZUS study for the City of Boston). Damaging earthquakes also affected New York City in 1737 and 1884, and Newburyport, MA in 1727. Paleoseismological investigations have shown that the Newburyport area, which is located only 50 km from downtown Boston, also experienced a strong earthquake about 2,000 years ago (Tuttle et al., 2003).

The seismic hazard in the NEUS is compounded by the low attenuation rate of seismic waves in the northeast. Historically, cities in the NEUS have suffered damage from strong earthquakes centered even hundreds of kilometers away, so studies of the seismic hazard of the major NEUS urban areas demand an understanding of the seismotectonics, strong-motion excitation and propagation characteristics, and earthquake probabilities throughout the entire NEUS region as well as in nearby Canada.

At the present time, we still only have a very general understanding of where and how often strong earthquakes occur in the NEUS. While we have good estimates of the average seismicity rates for the region as a whole, we are not yet able to make useful estimates of the earthquake activity rates of individual geologic structures. Also, we still have much more to learn about the generation and propagation of strong ground motions in the region. These questions are now taking on increased importance due to the interest of the U.S. Nuclear Regulatory Commission (USNRC) as it considers a number of new license requests for additional nuclear power plants in the central and eastern U.S. The following is a brief summary of some of the important research questions that can only be addressed by continued, improved and expanded earthquake monitoring in the NEUS.

Improved understanding of historic and prehistoric seismicity in the NEUS: Ebel et al. (2000) argued that some or much of the small modern earthquake activity of the NEUS may be aftershocks of strong earthquakes that took place hundreds or thousands of years ago.

Identification of seismically active structures: Continued and improved earthquake monitoring is needed to help identify and delineate those geologic structures that are seismogenic and capable of hosting a future large earthquake.

Determination of earthquakes rates throughout the NEUS: The rates of earthquake activity in individual seismic zones must be estimated from the routinely detected seismicity at all possible magnitude levels.

Earthquake forecasting in the NEUS: Studies such those of Ebel and Kafka (2002) and Kafka (2007) can be used as a basis for forecasting earthquake probabilities in the region; continued earthquake monitoring is important to test these ideas on earthquake forecasting.

Earthquake source studies: Continued earthquake monitoring is needed to enlarge the database of earthquake source parameters such as focal mechanisms, time functions, and stress drops for earthquakes of all sizes and at all locations.

Strong-ground motion generation and attenuation in the NEUS: New instrumental recordings of strong-ground motions in the NEUS, especially near-source recordings, are needed to improve the current NEUS strong-motion attenuation relations and for calibration of ShakeMaps.

Strong ground-motion site effects in the NEUS: Many cities and towns in the NEUS are sited on soft soils. It is important to obtain instrumental measurements of actual earthquake ground motion on the soft soils as well as on nearby bedrock outcrops in the NEUS urban areas to provide quantitative estimates of amplification; seismic amplification estimates are needed to accurately assess seismic hazard in the northeast.

3.0 Changes Implemented to the NESN in this Reporting Period

During the current reporting period (2007-2010) our main goals for the NESN network were to begin implementing the ANSS panel recommendations for improved instrument siting, to ensure that all of our data recording and processing systems were upgraded with the latest software versions, to implement contingency planning to ensure continuity of data collection in the event of power failure, to upgrade and strengthen our data collection system, to leverage partnerships for improved seismic monitoring throughout the region, and to coordinate with our stakeholders to implement their advice for improved monitoring in the Northeast region. In addition, we added three new seismic stations to the network, and we engaged in negotiations with several partners for external support of the network from non-USGS sources.

Three new stations were added during this period. In June 2008 we installed station WSPT (Westport, CT), located on the grounds of the Rolnick Observatory. This is an astronomical observatory with a small, part-time staff enthusiastic about joining our network and helping to keep the station running. In addition to providing the site free of charge, the observatory is providing free power and internet connection to host the station. In return, we are providing the observatory with a digital helicorder web gif of the station's data, which is to be used for educational purposes. The station location (Westport, CT) will improve our ability to locate earthquakes in southwestern New England. The second new station, ORNO (University of Maine, Orono) was installed in March 2009. All of the equipment for this station (Reftek RT-130 and Guralp CMG-40T) was purchased by the university with our guidance. A vault was constructed in the unfinished basement of a building on campus. The vault was dug down to within a meter of bedrock and the instrument installed. This station will improve our locations for earthquakes in Bar Harbor and vicinity. And finally, in July of 2008 we began importing a real-time continuous data stream from TA station TCHZ on Cape Cod; these data have been integrated with the NESN automatic location system. In 2009 station BRYW (Bryant University, RI) was resited to a quieter location on campus, and this has resulted in a much improved performance. In addition to these new stations, we have been working with staff at the University of New Hampshire Durham to help them purchase and install an NESN station. They have included a pier in the design of a new Earth sciences building currently being constructed, and they were working to secure funds for the purchase of a seismometer and seismic recorder in 2009. Also, we have been working with the New Hampshire state geologist, Dr. David Wunsch, for purchase of between 2 and 4 new seismic stations to be installed in that state. Dr. Wunsch has been able to get the procurement request through the first round of budget cuts.

In addition to the station upgrades outlined above, we upgraded many of our stations to the newest version of Reftek firmware, and we upgraded and strengthened our data collection and processing system. We replaced three computers of the NESN collection system with new machines purchased by Boston College. We also accepted donation of a new SunFire E280R server and (6) Dell Linux blades, which have been incorporated into the NESN processing system. The E280R server was upgraded to the latest version of Solaris (Solaris 10). We upgraded the primary UPS units used to backup the data collection system to APC Smart units with remote monitoring and text page capability. We upgraded the RTPD server software on the primary data collection machine, and upgraded all Earthworm servers to the latest version (v7.3).

In addition to these changes, we upgraded our interactive location software to make it more robust, and added a Big Brother monitoring and paging system. The Big Brother software polls all of the machines and all of the processes that comprise the NESN data collection and processing system, every 10 minutes (this is configurable), and the system pages NESN staff if any machines or processes have died. Using the new system has greatly reduced the amount of time any process (e.g., heli_ewII) has been down. During this period we completed archive of all past event waveform data with instrument response in SEED format at the IRIS DMC and we established real-time continuous data feed with IRIS DMC and hence we now maintain a full archive of all NESN data in SEED format at the DMC. In addition, we added online capability to search the NESN catalog going back to 1990 and added the capability to search for located blasts. And finally, during this period Boston College upgraded Weston Observatory's internet network to high-speed fiber optic which has greatly improved the speed and robustness of our data communication system.

4.0 Present Status of the Weston Observatory NESN

4.1 Current NESN Stations and Data Collection

The Weston Observatory NESN presently comprises 14 broadband and 2 strong-motion seismic stations distributed throughout the New England region (Figure 1), along with one cooperating station on Cape Cod. The broadband NESN stations are all equipped with 3-component Guralp CMG-40T seismometers with a flat response to ground velocity between 30 Hz and 30 sec and Reftek 130-01 dataloggers that provide 24-bit digitization. Currently all stations are sampled at 40 Hz and transmitted in real-time via ethernet link to Weston Observatory. Instrument responses are documented, both locally at the NESN Data Center and at the IRIS DMC, in dataless seed format. The RT-130 dataloggers stream continuous seismic data in real-time over the internet to a primary Reftek Transport Protocol (RTPD) server at Weston Observatory. In addition to the stations that WO operates, the NESN data collection system receives real-time data from approximately 20 additional stations in the region (Figure 1). The RTPD server at Weston Observatory communicates with several software agents that monitor the network status, monitor the state of health of each station (e.g., GPS clock status, power) and report any delays in data reception. Reftek data packets are archived locally and are passed in real-time to the primary Earthworm server at Weston Observatory.

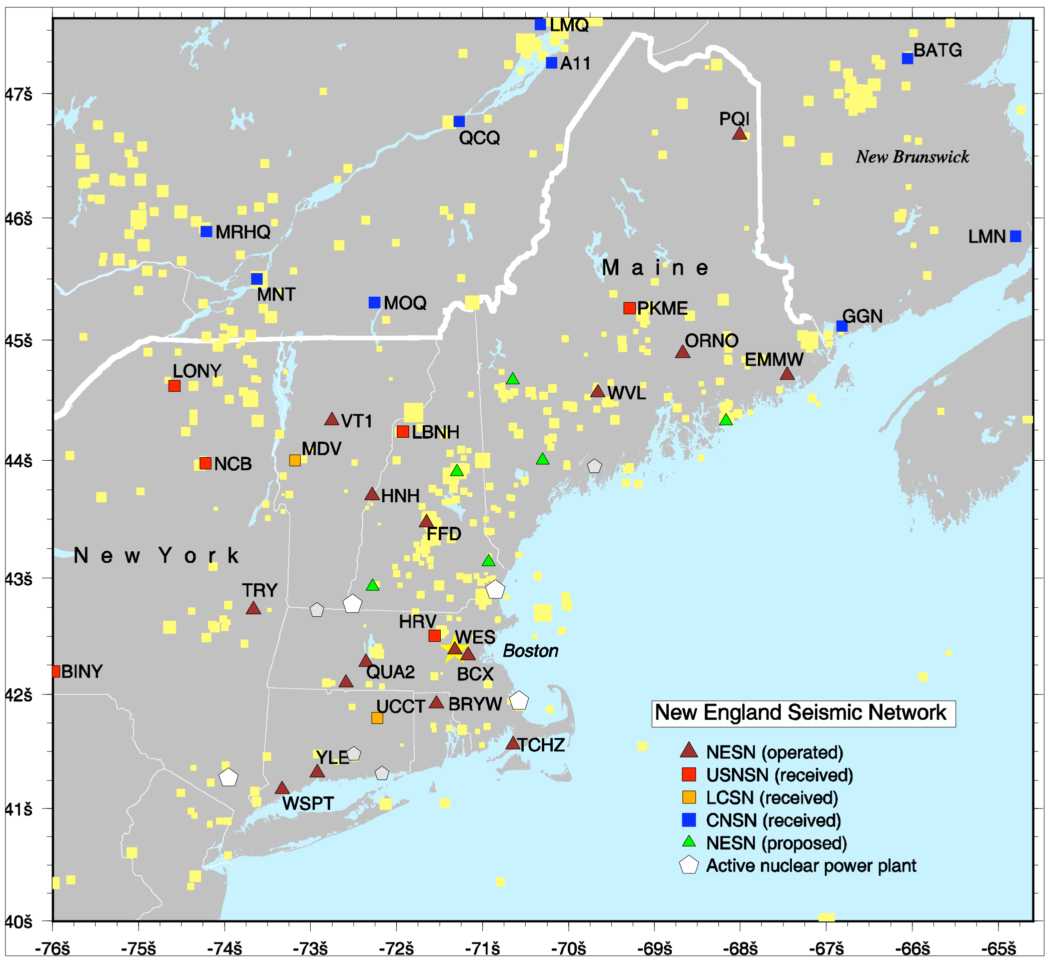

Figure 1. Map of the Northeast region showing stations operated by the New England Seismic Network (NESN), as well as those received in real-time from neighboring networks: USNSN, LDEO and CNSN. Also shown are recent seismicity (yellow squares) and active and deactivated nuclear power plants (pentagons).

The implementation of the Earthworm system across various computers and platforms at Weston Observatory has been designed in a way to provide a high degree of data reliability and redundancy (Figure 2). In order to ensure against overload and subsequent system failure, the primary Earthworm server at Weston Observatory is dedicated solely to the import and export of waveform packets in real-time (no other processing is performed on the primary machine). The primary Earthworm server: (1) Imports the NESN station waveform data from the local RTPD server; (2) Imports waveform data from all non-NESN networks within and surrounding the NEUS region (USNSN, LCSN and CNSN); (3) Exports all waveform data to two secondary Earthworm servers at Weston; and (4) Exports all NESN waveform data to the USGS NEIC, to LDEO and to the GSC. The primary server is hosted on a Sun Solaris computer backed up by a local UPS, which in turn is backed up by an industrial-grade diesel generator able to power the entire observatory for 24-hours before needing refueling. A second Sun computer has been configured with the necessary software to replace the primary server in the event of machine failure.

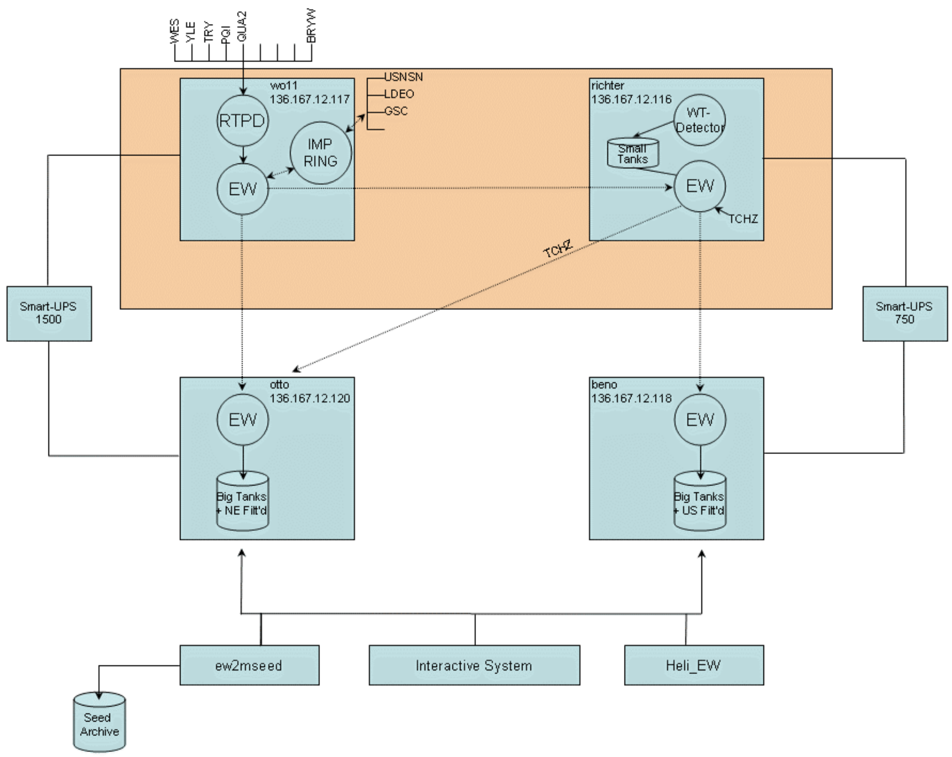

Figure 2. Schematic of current NESN primary data collection system.

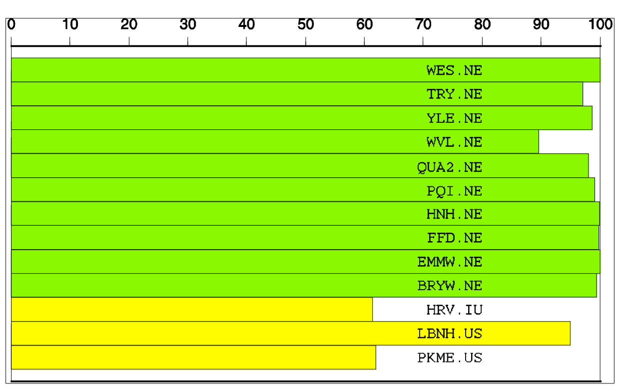

Figure 3. Percentage uptime for NESN (green) and USNSN (yellow) stations for the 3.5 year period 1/1/2006 – 7/6/2009.

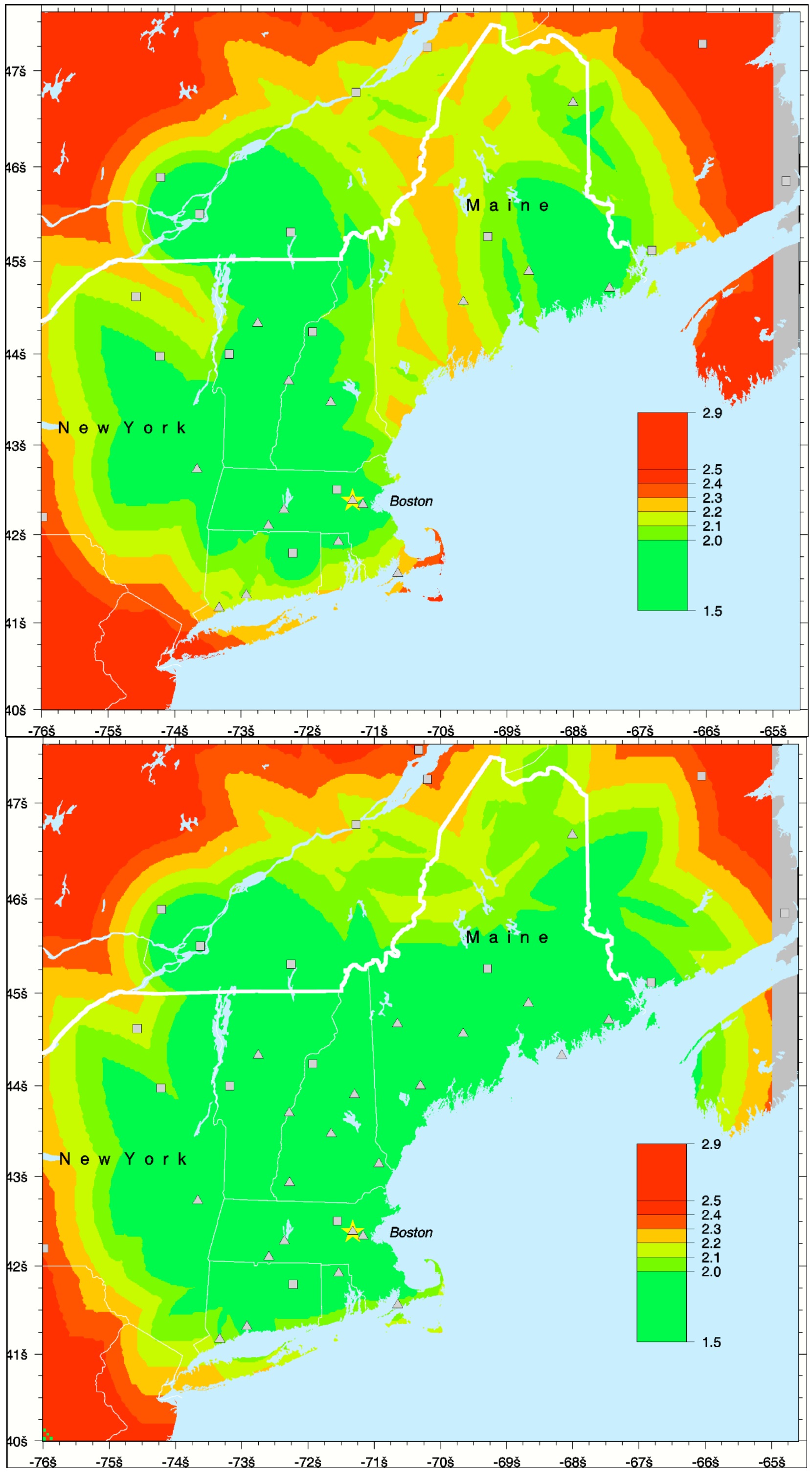

Figure 4. Estimated current minimum detection threshold (mLg) by the New England Seismic Network (top), and with the addition of 6 proposed stations (bottom).

Currently the majority of NESN stations are located in the basements of university buildings rather than in dedicated, outdoor, stand-alone vaults as general seismological best practices dictate. The decision to put the NESN stations at these sites was made a number of years ago due to budgetary constraints; by leveraging free power and internet offered by our university partners, we have been able to do a good job of monitoring earthquakes in New England at a minimal cost. Because our stations have hard-wired AC power and ethernet communications, our network has nearly perfect uptime, in contrast to the ANSS backbone stations in our network which provide higher quality seismic data but suffer long periods of downtime due to power and communications outages (Figure 3). However, buildings are not an ideal location for sensitive seismic sensors as they result in a large increase in cultural background noise and numerous noise transients that degrade the quality of data recorded. This impedes our ability to meet the ANSS Performance Standards for smaller earthquakes. In order to counteract this we designed and implemented a wavelet-transform based automatic detection system that uses the empirically determined noise levels at each station to optimize detection and identification of low signal-to-noise seismic events (Ebel 2006). In addition, as described below, we have received an ARRA grant to construct broadband vaults for the noisiest sites over the next 2 years.

Recent Improvements. During the past 1-2 years our main goals for the NESN network were to begin implementing the panel recommendations for improved instrument siting (see Stimulus Upgrades below), and to ensure that all of our data recording and processing systems were upgraded with the latest software versions and were robust. In addition, we added two new seismic stations to the network, and we continued to pursue several negotiations for external support of the network from non-USGS sources. As mentioned above, two new stations were added in 2008. The first is WSPT (Westport, CT), located on the grounds of the Rolnick Observatory, an astronomical observatory with a small, part-time staff who are enthusiastic about joining our network and are committed to keeping the station running. The second new station is ORNO (University of Maine, Orono). All of the equipment for this station (Reftek RT-130 and Guralp CMG-40T) was purchased by the university with our guidance and a vault was dug down to within a meter of bedrock. This station will improve our locations for earthquakes in central and southern Maine.

Stimulus Upgrades. During the period 09/01/09 – 09/11/11 we have been awarded ARRA funding to upgrade 13 of the NESN stations. At all stations the broadband sensors will be upgraded to even broader band Trillium 120's and the Reftek dataloggers will be upgraded to 6-channel models to permit the recording of three additional channels of strong-motion data. In addition, for 5-7 of our stations we will construct ANSS-standard vaults for the seismic sensors; the remaining stations, many of them located on dedicated piers inside buildings, will have insulation covers constructed for them that will improve coupling to the pier and will reduce noise at the highest and lowest frequencies. These upgrades will improve our detection and location threshold and move us closer to meeting the ANSS performance standards for all of New England. In December 2009 we upgraded station QUA2 (Quabbin Reservoir) with an ANSS-style vault and a Trillium 120PA broadband seismometer. The combination of dedicated vault and low-noise broadband seismometer has resulted in a much more sensitive station with a lower background noise, as evidenced by improved PDF noise plots.

Detection Thresholds and New Sites Identified. Figure 4 shows the estimated minimum location threshold for the New England region – that is, the minimum magnitude (mLg) for which we can confidently locate an earthquake with an accuracy of about ±5 km, as a function of location within New England. This calculation is based on empirical noise levels at each station and the requirement of achieving a minimum signal-to-noise threshold at a minimum of 4 stations in order to determine a location with acceptable accuracy. The noise levels used were those typical of summer and hence represent the lowest expected noise levels of the year; our minimum detection threshold will be worse (i.e., higher) in winter months when natural noise levels due to winds, surf, etc., are higher. Once we perform the scheduled ARRA upgrades to several of the stations, the situation will improve as sites with newly constructed vaults will have lower noise levels and hence a lower detection threshold. However, there will still be regions of New England with poor detection and location threshold that coincide with high seismicity (Figures 1 and 4).

The minimum earthquake location threshold is not uniform across New England because of our sparse station coverage. In particular, there are regions in central, western and southwestern (coastal) Maine, eastern New Hampshire, and southern Connecticut and Rhode Island where our minimum location threshold is several tenths of a magnitude unit higher than our targeted minimum threshold of mLg=2.0. Because of the low-attenuation of seismic waves in the northeast and the high population density, earthquakes below magnitude 3.0 can be felt over a surprisingly large area, and earthquakes as small as 1.0 can be felt in the region. Thus, our minimum uniform location threshold target (2.0) is larger than the minimum felt threshold. Figure 4 (right panel) shows the estimated improvement in minimum location threshold that would result from adding 6 new stations at key locations. In Figure 4, we have identified the locations where: a.) A new station would make the greatest contribution towards meeting the ANSS Performance Standards for minimum magnitude detection threshold; b.) A proposed site coincides with patterns of high seismicity and fills a gap in network coverage; and c.) A new station would have the highest likelihood of being funded externally through non-USGS sources. With this in mind we identified 3 station locations in Maine that would fill the gaps in detection threshold in southern and western Maine (Figure 4) and would significantly improve location accuracy. As discussed in section 4.4, we are working with stakeholders in Maine to identify potential sources of external funding for these sites. We also identified 3 site locations in New Hampshire that would improve detection threshold there and we are currently working with several stakeholders in NH to help them secure state funding for these stations (see section 4.4).

4.2 NESN Data Analysis System

The seismic data from the NESN stations along with the received LCSN, CNSN and USNSN stations are processed both automatically in near-realtime and later by the on-duty seismologist at Weston Observatory. Weston Observatory operates an automated wavelet transform event detection, identification and location system written by John Ebel (Ebel 2006). The automated system is designed to handle the unique aspects of earthquake monitoring faced by the NESN in New England: a sparse, widespread seismic network; earthquakes scattered throughout the region with no one area of focus; sites with frequent transient noise bursts (due to vehicles, footsteps, etc.); and the necessity to pick arrival times from emergent body-wave phases in order to accumulate sufficient arrivals times for constrained earthquake locations.

In addition, an entirely new interactive earthquake analysis, location and notification system has been implemented at Weston Observatory and has reduced considerably the time required for an analyst to review and post an event to the NEIC. When the automated system detects an event, it pages all members of the NESN duty staff and creates an earthquake event id that is passed on to the interactive system; the on-duty seismologist is then able to use the interactive system (from any computer with an internet connection and web browser) to quickly review the queued up event, adjust the picks as needed, relocate the event and post the reviewed location and magnitude to the USGS NEIC, typically within 30 minutes of an event.

(i.) <u>Automated Earthquake Detection and Notification System</u>

The system that has been developed and now operates at Weston Observatory for the NESN is an expansion and improvement of the wavelet-transform (WT) event detector and identifier that was developed by Gendron et al. (2000) for computing event locations and magnitudes for sparse networks (Figure 5). The automated system computes a discrete WT to 8 scales using the latest data received for

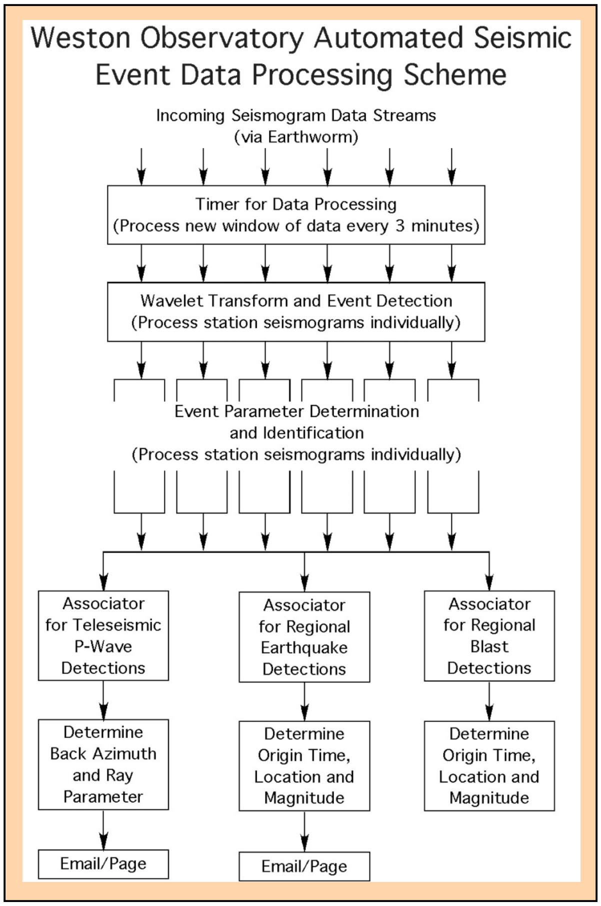

Figure 5. Flowchart of the automated data processing scheme at Weston Observatory

each station. In the event of a detection, the software uses a Bayesian scheme to calculate the probability that the detection was a teleseism, a regional earthquake, a local earthquake, a quarry blast, the Rg wave only from a quarry blast (a common detection in New England), or transient noise at the station.

Once the single-station event parameters and event identification probabilities have been determined, this information is sent through a bank of three different event associators that associate the event detections from different seismic stations. If the data from 3 or more stations associate, the event is located and Lg and coda magnitudes are computed and the event information is automatically sent via e-mail and SMS text page to Weston Observatory staff, NEUS stakeholders and other government officials on a need-to-know basis. Typically for small local earthquakes (less than magnitude 4.0), this information is sent out within 3-7 minutes of an event, meeting the ANSS standard for automated hypocenters and magnitude determinations in most cases.

An additional benefit of the improved system to automatically detect, identify and locate seismic events is that the number of small earthquakes found during routine NESN data analysis has significantly increased during the past few years. Currently, there are a total of about 2,000-3,000 event detections each day for all the seismic stations received by Weston Observatory. Because the wavelet-transform event identification and association system does an excellent job of discriminating real events from noise transients, only a few dozen of these detections need to be examined by an analyst, and a large number of them are indeed local earthquakes, quarry blasts, or teleseisms. Furthermore, during the summer months an average of about 10 quarry and construction blasts are detected each day in the NESN region, and those events must be discriminated from local earthquakes. As Table 1 shows, the number of local and regional earthquakes detected by NESN has increased markedly since the development of the wavelet-transform detection and identification system.

(ii.) <u>Interactive Earthquake Location and Reviewed Event Notification System</u>

When the automated system detects an event and issues a notification page, or when a felt report is communicated to the duty seismologist, either through Massachusetts Emergency Management (MEMA) or directly from the public, the NESN duty seismologist must manually review the seismic data to provide confirmation. To aid this, an entirely new interactive earthquake analysis, location and event notification system was developed and implemented at Weston Observatory over the past several years. We needed a robust system that would allow waveform picking, earthquake location, magnitude determination and event submission via QDDS/EIDS post, from any location (e.g., from home). We assembled a system of software that is: free, likely to receive continued support from the seismic or, preferably, larger internet community, and modular. Modularity is key to our design because it ensures that if one component of our interactive processing system becomes obsolete, we can insert a suitable replacement with few modifications to the other modules, ensuring that the entire system can be maintained and adapted with minimal effort.

Table 1.

Number of Earthquakes Centered in New England Detected by Weston Observatory from October 1, 2001 to September 30, 2009

Year	Total No. Earthquakes	# M >= 2.0 Earthquakes	# M < 2.0 Earthquakes
10/1/08-8/31/09	40	9	31
10/1/07-8/31/08	31	16	15
10/1/06-8/31/07	45	10	34
10/1/05-9/30/06	43	8	35
10/1/04-9/30/05	15	5	10
10/1/03-9/30/04	7	5	2
10/1/02-9/30/03	9	7	2
10/1/01-9/30/02	17	12	5

The interactive system allows Weston Observatory staff to quickly pick waveforms, locate an event, post the solution to USGS NEIC via QDDS/EIDS, archive the event summary, update the online NESN event catalog and maps, and notify New England stakeholders, including state officials, via both text page and e-mail, from any remote machine capable of running a web browser. Coupled with the improved automated detection, location and paging system described earlier, the new interactive system has markedly decreased the time required for Weston Observatory staff to review and post an event so that for most earthquakes within New England, we regularly post reviewed solutions to USGS NEIC within 30 minutes of an event, even at night and on weekends.

4.3 NESN Data Delivery and Archiving

Following a seismic event, Weston Observatory computes a large number of automatic and interactive earthquake information and data products for official and public distribution. With our new interactive data analysis system, we are typically able to post (via QDDS/EIDS) event information (location and magnitude) to USGS NEIC within 10 to 30 minutes of an event. Many of our important stakeholders – e.g., state emergency managers, state geologists, USACE – are notified of a reviewed event by email and text page sent directly through our interactive location system. Since 1994 Weston Observatory has had a memorandum of understanding (MOU) with the Massachusetts Emergency Management Agency (MEMA) concerning all felt earthquakes in the New England region. According to the MOU, whenever a felt earthquake is reported to the authorities of any New England state, that information is relayed to MEMA. MEMA is charged with contacting a seismologist at Weston Observatory, who then verifies the occurrence of an earthquake. In an effort to provide rapid information in case of a felt or damaging earthquake, Weston Observatory has established a 24/7 on-call schedule to review and process earthquake data. Each week, one of four Weston Observatory seismologists assumes the role of on-call seismologist and is responsible for reviewing and locating all seismic events at any time of the day or night. The NESN duty seismologist must also coordinate earthquake response with both the MEMA duty personnel and the USGS-NEIC duty seismologist. We have provided both MEMA and NEIC with our on-call schedule and a hierarchical list of NESN duty seismologist contact information.

Weston Observatory also provides earthquake information directly to the HHAN (Health and Homeland Alert Network Protocol), a new, robust emergency alert system that distributes emergency information throughout all six New England states. And finally, with the new interactive analysis system, event summary information is instantly posted online at the NESN Data Center site (http://quake.bc.edu:8000) for public notification. The NESN recent events catalog is automatically updated with the latest event, along with a link to an auto-generated location map, and the event is displayed on the New England Real-Time Earthquake Monitor.

At the end of each month, Weston Observatory electronically submits all final event solutions for that month to the CNSS Composite Catalog. After the end of each calendar quarter, Weston Observatory publishes all of its earthquake locations, phase readings, and amplitude information in quarterly seismicity reports via the Weston Observatory web page. These quarterly reports of seismicity contain the final, fully reviewed event locations and magnitudes for all earthquakes in New England and vicinity, and they also contain the Weston Observatory phase and amplitude readings for regional earthquakes that were centered outside of New England. Annual summaries of the seismic activity detected by the NESN are submitted to the USGS by Weston Observatory and are posted on the USGS web site http://erp-web.er.usgs.gov/ under the link Reports.

4.4 Leveraging Partnerships in New England to Coordinate Monitoring Resources

Weston Observatory is working with partners in New England to establish a cooperative program of earthquake monitoring that will benefit both the stakeholders and Weston Observatory. Weston Observatory is continuing to work to procure and install new broadband stations in Maine (at the U. of Maine at Farmington and at the U. of Southern Maine in Gorham) and two broadband new stations in New Hampshire (at the U. of New Hampshire in Durham and at Keene State College). In all cases, we are asking support from the local university or the state to purchase the station equipment, which would be installed and operated by Weston Observatory with the data transmitted to Weston Observatory for inclusion in the ANSS-NE data stream. For all of these proposed stations, the requested equipment is for broadband seismic sensors with Reftek 130 data loggers and digital radios to telemeter the continuous seismic signal from an isolated ANSS-style vault. If sufficient funding can be acquired, a strong-motion sensor will also be installed as part of the station configuration. In addition, the New Hampshire state geologist (Dr. David Wunsch) has submitted a request for funding for 4 new broadband seismic stations within the NH state budget capital request. In addition to these sites, we will work closely with Earthscope as they roll out the TA and BigFoot Arrays into the Northeast over the next few years. In particular, we will look for external partnerships and sources of funding to adopt TA stations in key monitoring locations in New England (e.g., northwestern Maine).

Weston Observatory has also been engaged in discussions with stakeholders in New England concerning the acquisition of strong-motion seismic data in the region. The US Army Corps of Engineers (USACE) operates 34 digital strong-motion instruments at various dams in New England. Currently, Weston Observatory and the USACE in Concord, MA are negotiating a Blanket Purchase Agreement (BPA) for Weston Observatory to receive and process the strong-motion data from the USACE dams in New England. We expect to have the BPA in place sometime in 2010. Weston Observatory also is seeking the installation of strong-motion stations at other independently-operated dams in New England. Recently, Weston Observatory was contacted by FirstLight Power, a utility company that operates a hydroelectric facility on the Connecticut River in Northfield, Massachusetts, and asked to submit a proposal to install strong motion instrumentation at the dam. We have submitted a proposal to First Light that includes setting up communications so that the continuous strong-motion data stream can be imported into the NESN processing system. In addition to these stakeholders, Weston Observatory will work to coordinate collection and dissemination of strong-motion data with the National Strong-Motion Program (NSMP).

Weston Observatory has submitted a proposal to the Massachusetts Emergency Management Agency requesting funding to defray some of the costs of seismic network operations in New England. The requested funding will allow Weston Observatory to integrate more earthquake information into the new HHAN emergency information distribution system and to greatly expand the number of important stakeholders in the region who will receive the direct delivery of earthquake information via email and text pages.

4.5 Portable Instrument Pool

Weston Observatory currently maintains a pool of four Reftek RT-130 dataloggers and Guralp CMG-40T seismometers for use in aftershock surveys and temporary seismic deployments. In addition, WO has a Nanometrics Orion seismograph with a CMG-40T sensor for portable deployment. All portable instruments were purchased with Boston College funds. The portables are currently deployed in the Newburyport, MA area in a temporary experiment to look for residual microseismic activity associated with the 1727 earthquake and to refine routine NESN locations in that area. These data are being analyzed by a Boston College undergraduate as part of her senior honors thesis. Should these instruments be needed for an aftershock deployment following a strong earthquake, they can be gathered from their current sites and redeployed within 1-2 days.

4.6 Earthquake Outreach and Education at Weston Observatory

Weston Observatory has a strong commitment to public outreach and to seismology education. WO is open to the public for tours, and many people visit the facility each year. Seismic equipment can be viewed and literature about earthquakes, seismic monitoring, the ANSS, and other geoscience topics is available. Weston Observatory hosts a highly-acclaimed evening colloquium series on geoscience topics for the general public that culminates each June with our annual open-house. A listing of the 2009-2010 colloquium series presentations can be found at http://www.bc.edu/research/westonobservatory/educationlist/lectures.html.

The Boston College Educational Project (BC-ESP: http://www2.bc.edu/~kafka/SeismoEd/BC_ESP_Home.html) is another educational venture that utilizes seismic data recorded by the NESN of Weston Observatory and is led by Professors Alan Kafka, John Ebel and G. Michael Barnett (Boston College Lynch School of Education). Under the BC-ESP, middle schools and high schools in Massachusetts purchase an educational seismograph and computer for data digitization and display, and they also fund a Weston Observatory seismologist or graduate student to come into the classroom to run a series of classroom projects to teach the science of seismology. In just four years the BC-ESP has grown from 2 schools to over 20 schools. The program has become very popular in Massachusetts, and it is helping to raise the visibility of the Weston Observatory and its earthquake monitoring in the region.

A third public outreach program is provided by the NESN web pages. We have designed a digital helicorder display that can be customized for each of our partner institutions (e.g., universities throughout New England). Many of our contributing partners have set up computer kiosks in their lobby that feature the near real-time helicorder data from the seismic station that they host, displayed by a web server at Weston Observatory. Each station display is customized to include the host institutions logo, in addition to those for Weston Observatory and the USGS-ANSS (http://quake.bc.edu:8000/cgi-bin/NESN/24hr_heli).

4.7 Network Personnel

Funding levels for the NESN at Weston Observatory have limited the regional network staffing to a full-time network manager (Dr. Michael Hagerty) and a part-time seismic analyst (Anastasia Macherides Moulis). The system manager's duties include maintaining the operations of all of the NESN stations (including hardware repair and maintenance), siting new stations or moving existing stations, maintaining Earthworm and related data analysis systems, and constructing the data delivery web pages (such as http://quake.bc.edu:8000). He oversees production and verification of dataless seeds and noise PDFs for all NESN stations. The seismic analyst is charged with checking the most recent event detections for earthquakes or quarry blasts, locating and determining the magnitude of each earthquake that is detected, updating the data lists of earthquakes and quarry blasts detected by the NESN, archiving all of the event data, and preparing the quarterly seismicity reports. The PI on this project, Prof. John E. Ebel, also spends some of his time on seismic network operations, including supervising all of the operations and staff involved in the project and participating regularly in analyzing the earthquake data. In addition to guiding graduate students who carry out research using the NESN data, he is working to improve the automated WT system for event detection, identification, association, and location/magnitude determination. Dina Smith, a seismologist and Associate Director of Operations at Weston Observatory, maintains the Weston Observatory web pages, including the lists of recent earthquakes in New England and vicinity, the quarterly NESN bulletins, links to other seismic network operators, educational seismology links, and other information concerning earthquakes in northeastern North America and around the world. She also participates in the four-person rotating 24/7 duty seismologist roster. Finally, field specialist John Beck is working with Mike Hagerty on the NESN station upgrades that are being funded by an ARRA grant from the USGS; he is charged with supervising and coordinating vault construction and improvements at the remote seismic stations and will be assisted by a Boston College graduate student.

5.0 Reports and Dissemination of Information and Data

Weston Observatory provides annual reports on this project in a timely manner as required by the USGS. In addition, quarterly reports on the seismicity of the region as detected and processed by the NESN are prepared and posted on the Weston Observatory web site along with other pertinent earthquake information such as earthquake catalogs and maps and station metadata. Following any NESN station upgrades and/or configuration changes, the NESN metadata database is updated in a timely manner and a new NESN dataless seed file is made available with the updated response information. Weston Observatory posts its solutions to the QDDS/EIDS system and to the ANSS public web pages as soon as possible after earthquakes occur, and submits all of its waveform data to the IRIS DMC along with maintaining a local archive of waveform data. Weston Observatory cooperates in the timely exchange of waveform and parametric earthquake data with LDEO, NEIC, the GSC and stakeholders in New England. Finally, Weston Observatory is a well-known center for earthquake information in New England. Weston Observatory staff members are frequently interviewed by TV, radio, newspaper and magazine reporters. The Observatory maintains many displays in its building concerning earthquakes in New England as well as around the world. Each year Weston Observatory hosts over 500 visitors who tour the facility and collect information about earthquakes. All of these are means of disseminating information about earthquakes in the northeastern US and southeastern Canada.

6.0 Seismicity Summary

Figure 6 shows the epicenters of local and regional earthquakes recorded by Weston Observatory from February 1, 2007 to January 31, 2010. A total of 214 local and regional earthquakes with magnitudes from 0.3 to 4.2 were detected and located by the NESN stations, some of which were felt by those living near the epicenters. Also recorded throughout the time period of this report were some microearthquakes or other events that were possible earthquakes but with insufficient data to compute a location. Of the seismicity shown in Figure 6, there were 107 earthquakes centered in (or offshore of) New England. The largest New England earthquake during this time period was MLg 2.8 centered offshore east of Portsmouth, NH on March 9, 2008. According to Ebel (1984), New England averages about 2 earthquakes above magnitude 3.0 each year, and so the lack of any earthquakes of magnitude 3.0 or greater during the three-year period of this report represents an unusual lull in the stronger earthquakes in the region as compared to the long-term average.

There are several localities shown in Figure 6 where there was earthquake activity of some note during the period of this report. Arrow A points to an area near Rumford, ME, which had several small earthquakes during the time period of this report. In 1983 there was a magnitude 4.4 earthquake at nearby Dixfield, ME (Ebel and McCaffrey, 1984). The number of earthquakes shown on Figure 6 for the three-year period of this report represents the greatest rate of activity in this area since the 1983 earthquake. Arrow B points to a cluster of seismicity in New Hampshire just northwest of Newburyport, MA. The Newburyport area was the epicentral region of a magnitude 5.5 earthquake in 1727 (Ebel, 2000), and Ebel (2000) speculated that the 1727 earthquake took place on a NW-striking thrust fault. The seismicity at arrow B might be related to the 1727 earthquake and its causative fault. Arrow C points to seismicity in central New Hampshire, which remains the single most seismically active area in New England. This area is thought to have been the epicentral region of a strong earthquake in 1638 (Wheeler et al., 2001). Arrow D points to an area near Albany, NY, which experienced a swarm of small earthquakes in early 2009 and again in early 2010. Arrow E shows an area in western Vermont where several small earthquakes were reported during the time period of this report. Prior to 2007, this locality had experienced relatively little seismicity. Arrow F shows Littleton, MA, which experience an MLg 2.5 earthquake and MLg 0.9 aftershock on October 19, 2007. Littleton, MA is a suburb northwest of Boston, which on average has experienced a felt earthquake about once every 2½ years since the late 1970s. An MLg 2.0 earthquake was felt at Littleton on October 8, 2004, and that event was followed by a few small aftershocks. If the seismicity of this locality follows its average schedule, its next felt event should take place sometime in 2010. Finally, arrow G shows an offshore locality where two earthquakes were detected during the period of this report. The earthquakes at locality G are centered at the continental slope in an area where the continental shelf sediments are cut by a NW-SE trending trough. Whether these earthquakes represent normal tectonic activity or sediment slumping is not known. However, these and several earthquakes on Figure 6 S and SE of Long Island indicate that there is some offshore earthquake activity. If a strong earthquake can be centered at any of these offshore areas, the possibility of a tsunami due to the earthquake must be considered.

In the Final Report for USGS grant 04HQAG0020 (prepared in December 2006), it was noted that since the late 1990s the rate of earthquake activity in New England was significantly lower than it was during the late 1970s and early 1980s. The time period from 1980-1999 also was one when several earthquakes above magnitude 4.0 affected the region. Since 1989 the only earthquake in New England with $M \geq 4.0$ took place at Bar Harbor, ME in October 2006 (Ebel et al., 2008). For the time period from February 1, 2007 to January 31, 2010, the seismicity in New England continued to occur at a rate lower than that of the 1970s and 1980s, although it was higher than the rate of earthquake for the three years prior to February 1, 2007. From February 1, 2007 of January 31, 2010 there were 30 earthquakes with $M \geq 2.0$, or about 10 per year, and no earthquake was above M 3.0. For the time period from February 1,

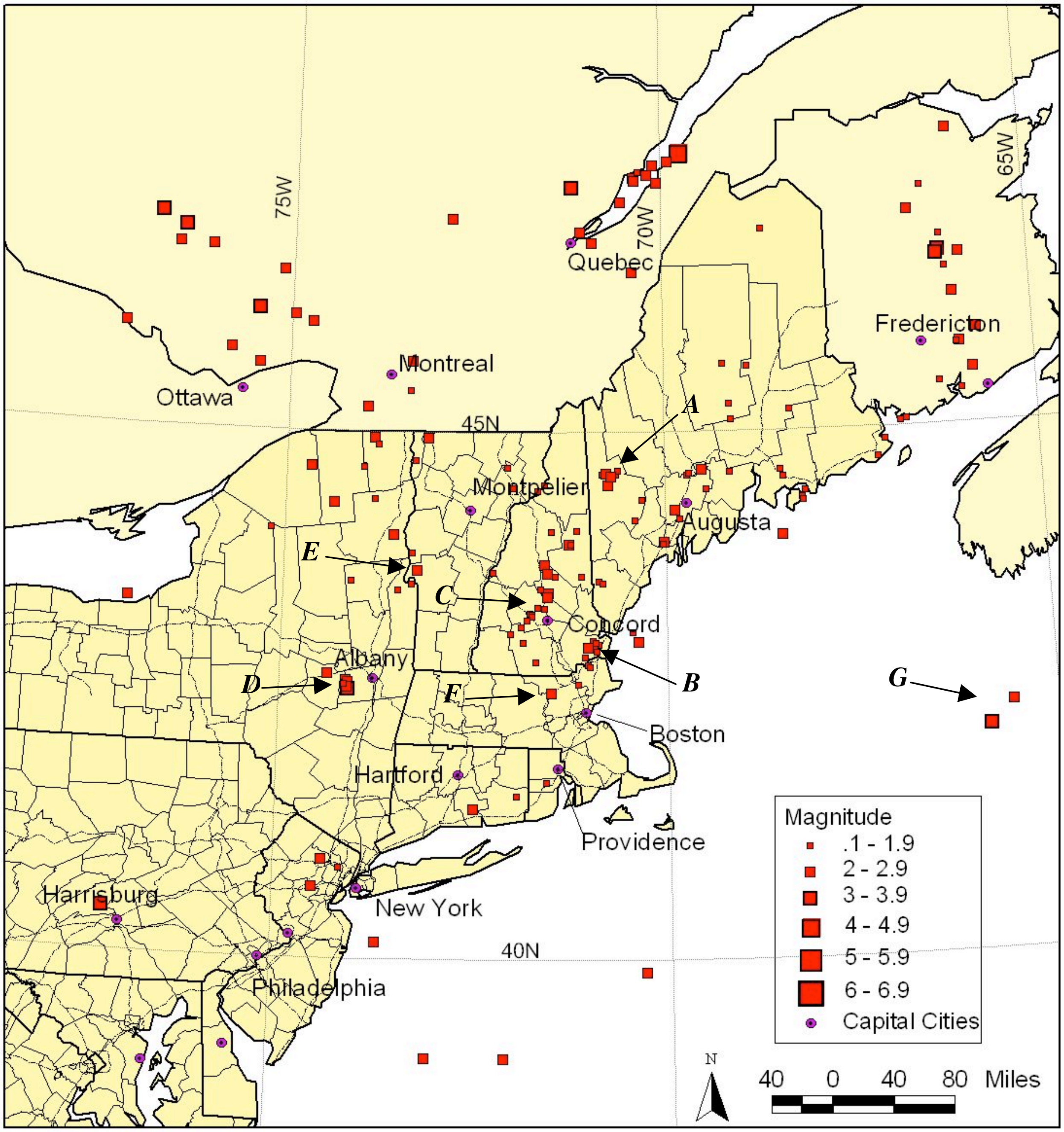

Figure 6. Seismicity of New England and vicinity from February 1, 2007 to January 31, 2010 as recorded by the seismic stations of Weston Observatory of Boston College. The arrows with letters show locations of earthquakes that are discussed in the text of the report.

2004 to January 31, 2007 there were 14 earthquake with M≥ 2.0, or about 5 per year, and there were 2 earthquakes with M≥3.0. According to Ebel (1984), from 1975 to 1982 New England averaged about15 earthquakes per year of M≥2 and about 2 earthquakes per year of M≥3. A chart of the annual numbers of earthquake of M≥2.7 (the approximate completeness threshold for this time period) since 1979 is shown in Figure 7. From Figure 7 it is clear that that since 2002 the annual rate of earthquake activity in New

England is significantly reduced compared to that from 1979 to about 1999. The higher rate of small earthquakes from 1979 and 1984 compared to more recent times corresponded to a time period when several earthquake with M≥5.0 took place in northeastern North America, and when several earthquakes with M≥4.0 took place in New England. This evidence may suggest that there is a higher probability of earthquakes with larger magnitudes in northeastern North American during time periods when there is a higher rate of small earthquakes throughout New England and vicinity.

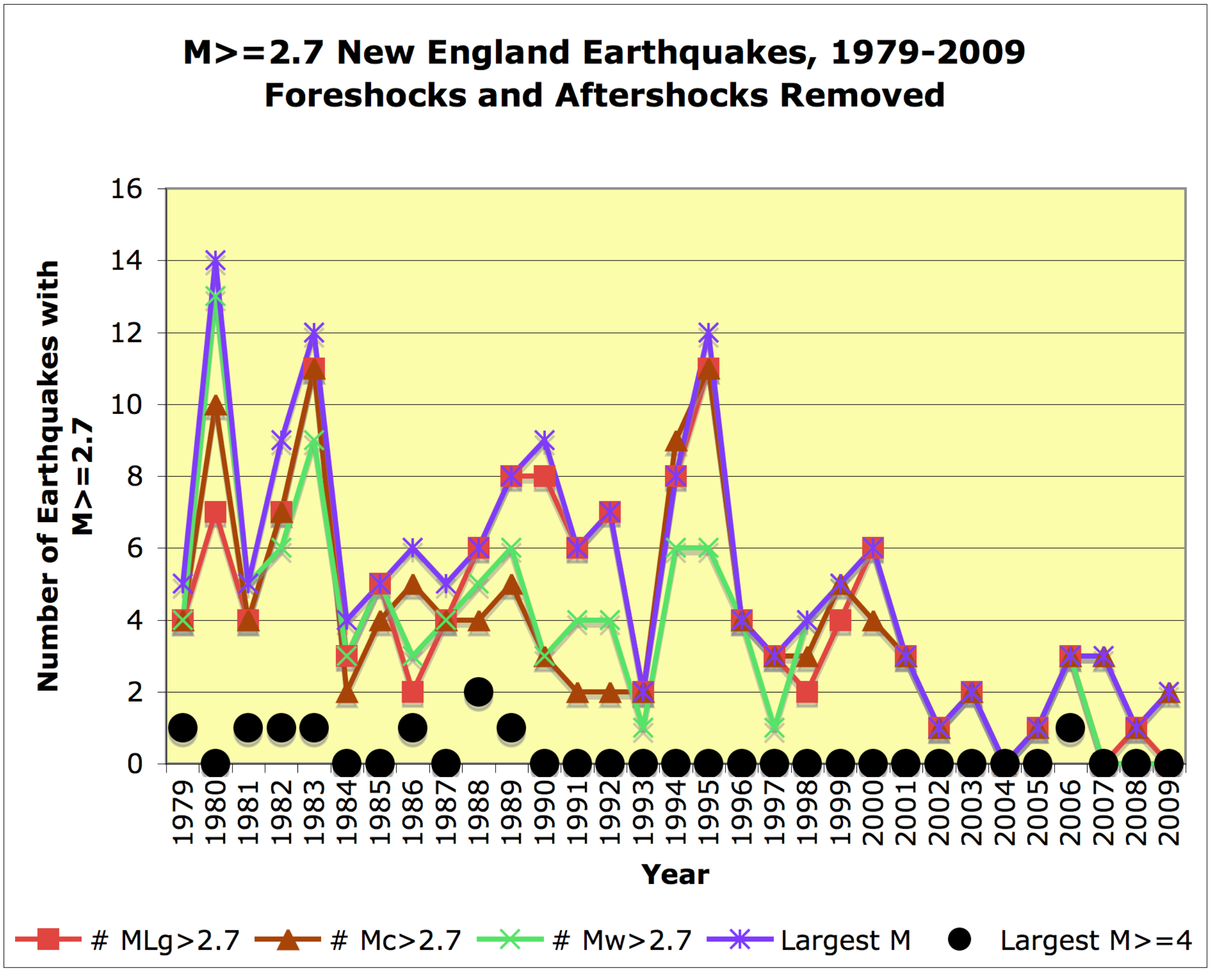

Figure 7. Histogram of the number of earthquakes per year with at least one magnitude type (Mc, MLg or Mw) of 2.7 or greater for New England from 1979 through 2009, along with the number of earthquakes each year where at least one of Mc, MLg or Mw was 2.7 or greater. Also plotted as the black dots is the number of earthquakes of largest magnitude M≥4.0 for each year. The highest rates of earthquake activity occurred in 1980, 1983 and 1995. Since 2000 the rate of earthquake activity has been reduced compared to the previous two decades.

7.0 Related Efforts

Weston Observatory has been involved in studying the earthquake activity in New England and vicinity for almost 80 years. Dr. John Ebel and Dr. Alan Kafka been involved in numerous studies of the earthquake hazards in the region, particularly in the Boston area. For example, a study of the recent Bar Harbor earthquake sequence was recently published by Weston Observatory scientists (Ebel et al., 2008).

Many people consult the Observatory and its web site for information on recent earthquakes, earthquake probabilities, past earthquake history and earthquake information. As a co-coordinator of the ANSS in the northeastern U.S., Dr. Ebel is in an excellent position to educate users in the region about the threat of earthquakes in the northeastern part of the U.S. Dr. Ebel and Dr. Kafka often appears in the media discussing earthquakes and earthquake potential in the NEUS. Also, they both have supervised numerous Boston College M.S. theses that have focused on the seismic hazard and seismotectonics of the New England region. From 2003 to 2009, NESN data have been used in 8 peer-reviewed papers, 6 MS theses and more than 20 conference abstracts that have been published or presented by faculty, researchers and students from Weston Observatory and the Department of Geology and Geophysics at Boston College.

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9.0 Publications Using Data from the New England Seismic Network

Ebel, J.E. (2009). Analysis of Aftershock and Foreshock Activity in Stable Continental Regions: Implications for Aftershock Forecasting and the Hazard of Strong Earthquakes, *Seismological Research Letters*, **80**, 977-983.

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10.0 Published Abstracts Using Data from the New England Seismic Network

Ebel, J. E. (2010). A Strategy for Siting Strong-Motion Instrumentation in the Central and Eastern U.S., *Seismological Research Letters***, 81**, 155.

Ebel, J. E. (2010). Analysis of Aftershock and Foreshock Activity in Stable Continental Regions: Implications for Aftershock Forecasting and the Hazard of Strong Earthquakes, *Seismological Research Letters***, 81**, 155.

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Ebel, J.E. (2009). The Search for Active Faults and the Assessment of Seismic Hazard in the Northeastern U.S., *2009 Abstracts with Programs, 44th Annual Meeting, Northeastern Section, Geological Society of America*, **41**, 82.

Ebel, J. E. (2009). Recent Earthquake Activity in New England: Implications for Regional Seismic Hazard, *Seismological Research Letters***, 80**, 166.

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Hertzog, J. T., and J. E. Ebel (2008). The Upper Mantle Seismic Structure of Northeastern North America, *Seismological Research Letters*, **79**, 135.

Kafka, A.L. and J. Taber, (2008). Earthquake Prediction and Forecasting: How Likely are Damaging Earthquakes in the Northeast US?, Workshop for science teachers, presented at meeting of *National Science Teachers Association*, Boston, MA March 28, 2008.

Braile, L.W., A.L. Kafka and J. Taber (2008). Shaking Up Classrooms with a Simple Seismograph: The IRIS Seismographs in Schools Program, Workshop for science teachers, presented at meeting of *National Science Teachers Association*, Boston, MA March 27, 2008.

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Ebel, J. E., Kafka, A. L., Moulis, A. M., Smith, D. M., and Barnett, G.M. (2007). The Boston College Educational Seismology Project (BC-ESP): "Inviting Students into the World of Science Research", *Seismological Research Letters*, **78**, 160.

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11.0 Presentations by Dr. John E. Ebel Using Data from the New England Seismic Network

Invited Presenter: "Earthquakes in New England", presentation to the North Shore Emergency Preparedness Symposium, Peabody-Essex Museum, Salem, MA, February 12, 2009.

Invited Presenter: Central and Eastern U.S. Seismic Source Update Project Workshop, organized by the Electric Power Research Institute, Palo Alto, CA, February 18-20, 2009.

Invited Presenter: “Prediction, Forecasting and Hazard Analysis of Earthquakes”, Risk Management Conference GCOR III, Boston, MA, April 23, 2009.

Invited Presenter: Workshop on the Next Generation Attenuation Relationships for the Eastern U.S., organized by U.C. Berkeley, May 13, 2008, Berkeley, CA.

Invited Presenter: Central and Eastern U.S. Seismic Source Update Project Workshop, organized by the Electric Power Research Institute, August 25-26, 2009, Palo Alto, CA.

Invited Presenter: “Earthquakes in New England”, Department of Geology, University of Maine, September 18, 2009, Orono, ME.

Presenter: Central and Eastern U.S. Earthquakes Workshop, organized by the U.S. Geological Survey, October 28-29, 2009, Memphis, TN.

Invited Presenter: “Statement on Earthquakes and Earthquake Hazard in New England”, presented at the Long Island Sound Liquefied Natural Gas Task Force Meeting, February 25, 2008, Connecticut State House, Hartford, CT.

Invited Commenter: “Earthquake Science & the 19th Century American Environment”, presentation by Conevery Valencius with comment by John E. Ebel, March 11, 2008, Massachusetts Historical Society, Boston, MA.

Invited Presenter: Workshop on the Next Generation Attenuation Relationships for the Eastern U.S., organized by U.C. Berkeley, May 13, 2008, Berkeley, CA.

Invited Presenter: Central and Eastern U.S. Seismic Source Update Project Workshop, organized by the Electric Power Research Institute, July 22-23, 2008, Palo Alto, CA.

Invited Presenter: Workshop on Mmax, organized by the U.S. Geological Survey, September 8-9, 2008, Golden, CO.

Invited Speaker: “Automated Monitoring of Earthquake Activity in New England Using Matlab”, January 31, 2007, Mathworks, Inc., Natick, MA.

Invited Speaker: Earthquakes, February 1, 2007, Massachusetts Highway Association, Randolph, MA.

Invited Speaker: Resource Acadia Workshop, Acadia National Park, June 2, 2007, Bar Harbor, ME.

Conference Organizer, Participant and Speaker: ANSS-NE Roundtable Meeting, September 17-18, 2007, Weston, MA.

12.0 Presentations by Dr. Alan L. Kafka Using Data from the New England Seismic Network

Invited Presenter: Use of Seismicity to Define Seismic Sources, Application in the Eastern North America Region, Central and Eastern U.S. Seismic Source Update Project Workshop, organized by the Electric Power Research Institute, Palo Alto, CA, February 18-20, 2009.

Invited Speaker: Where Do Large Earthquakes Occur in the Eastern United States? or: Reflections on the Holy Grail of Earthquake Predictions, IRIS Undergraduate Internship Orientation Week, New Mexico Institute of Mining and Technology, Socorro, NM, May 24-30, 2009.

Invited Speaker: Weekly lectures/presentations on Earthquakes and Seismology for 1st through 4th grade BC-ESP students at St. Peter School, Cambridge, MA, April-May, 2009.

Invited Speaker: Weekly lectures/presentations on Earthquakes and Seismology for high school BC-ESP students at Nashoba Valley Technical High School, Westford, MA, April-May, 2009.

Invited Speaker: Presentation to high school students from inner city schools in Newark, NJ for a science enrichment program at Rutgers University in Newark, July 14, 2009.

Invited Speaker: Presentation for graduating ceremony and annual Sea Lab Open House, New Bedford Public Schools, New Bedford, MA, August 14, 2009.

Invited Speaker: Educational Seismology: A Window into the World of Science Research for Students of All Ages, Weston Observatory Colloquium Series, December 10 and 17, 2008.

Invited Speaker: Educational Seismology Lecture/Presentation for ribbon cutting ceremony for BC-ESP seismograph at the John F. Kennedy Middle School, Natick, MA, October 14, 2008.